A COMPACT KILOWATT STORAGE RING EUV SOURCE BASED ON STEADY STATE MICROBUNCHING

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While this is a report on an EUV source, as accelerator physicists, we fully recognize there are many critical issues beyond the development of powerful EUV sources.

The technology of coherent radiation made a critical step with the invention of the FEL in 1971. FEL is a tremendous game changer. The trick is to “microbunch” the electron beam.

Microbunching is a wonderful thing. Two reasons to require microbunching:

- to raise the radiation frequency to Xrays
- to increase the power of radiation by a factor of *N*, the number of electrons in the microbunch.

With microbunching, the peak power of the FEL radiation is extremely high.

FELs have extremely high peak power, but low average power. FELs use linear accelerators, and linear accelerators have low repetition rates.

In contrast, traditional synchrotron radiation from a storage ring has high repetition rates, but the electrons all radiate individually, no enhancing factor of N. Neither does a plasma EUV source.

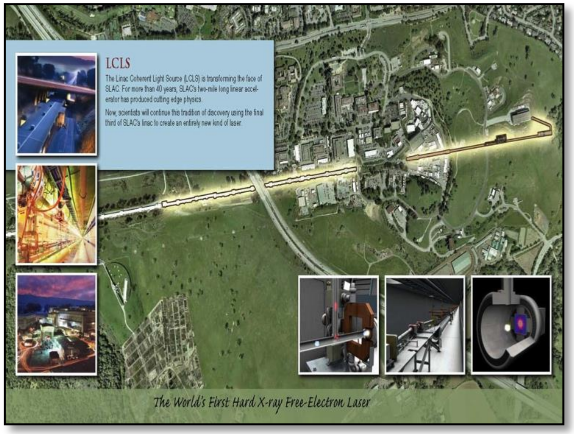
The next step in the development of high power coherent radiation sources requires BOTH,

- high peak power with the factor of N
- high repetition rate

For SSMB [Daniel Ratner, AC, 2010],

- High repetition rate ➔ storage rings
- peak power ➔ microbunch the beam

Can we combine the advantages of a high peak power device and a high repetition rate device?

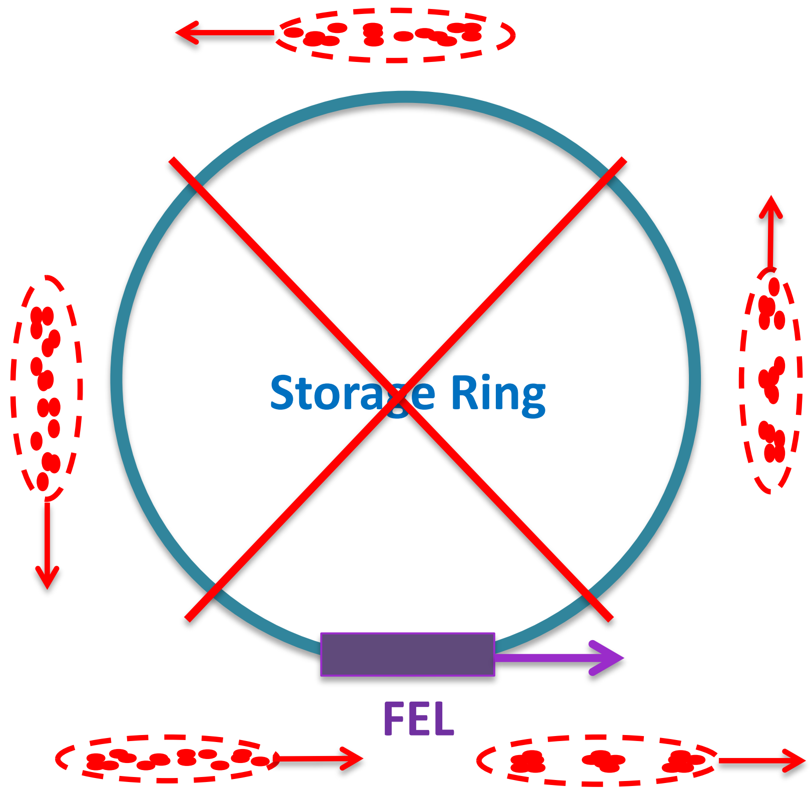


x

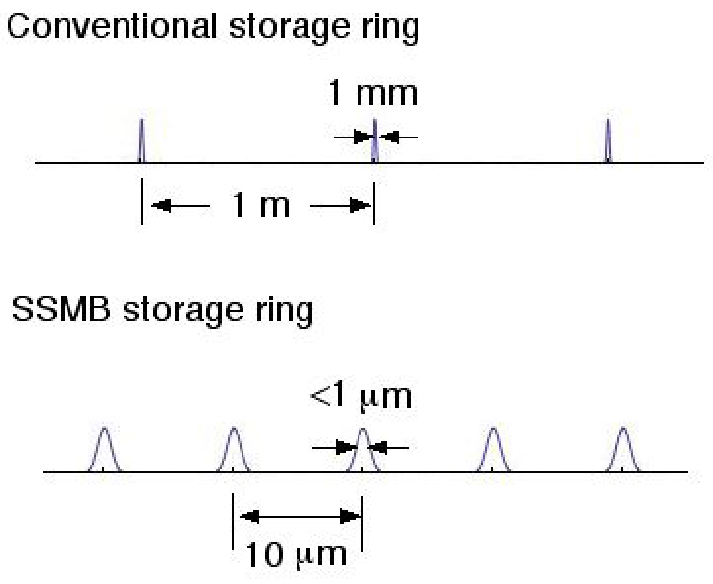
= ?

Simply inserting an FEL in a storage ring does not work.

It takes a few radiation damping times to cool the beam after each FEL passage, thus losing the high repetition rate of the storage ring.



The basic idea is to manipulate the beam's dynamics in a storage ring so that its distribution is not the conventional Gaussian with bunch length ~1 mm, but microbunched with each microbunch having length < 1 um so that all microbunches radiate coherently, gaining the factor of $N \sim 10^{5\text{-}6}$



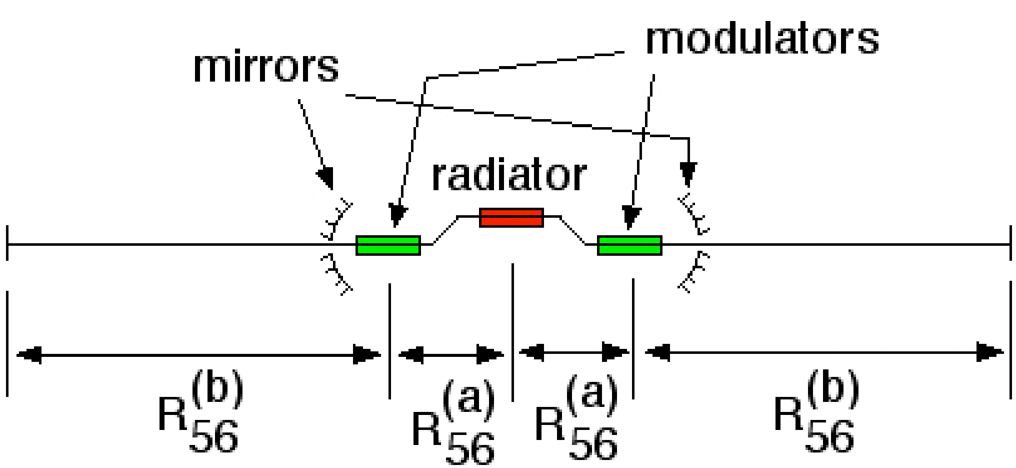
The trick of SSMB lies in finding a way to make the beam <u>microbunched</u> in the first place, and staying microbunched in the <u>steady-state</u> environment of a storage ring. ➔ "steady state microbunching''.

With the high repetition rate (~3 x 10^5 GHz), radiation per bunch passage is far weaker than an FEL (by 5-6 orders of magnitude). The electron beams are not disrupted by each passage through the radiator. This device is not an FEL.

It is $\left[N \sim 10^{5\text{-}6}\right]$ **x** $\left[\sim 3 \times 10^5 \text{ GHz repetition rate}\right]$ that makes SSMB a high power source.

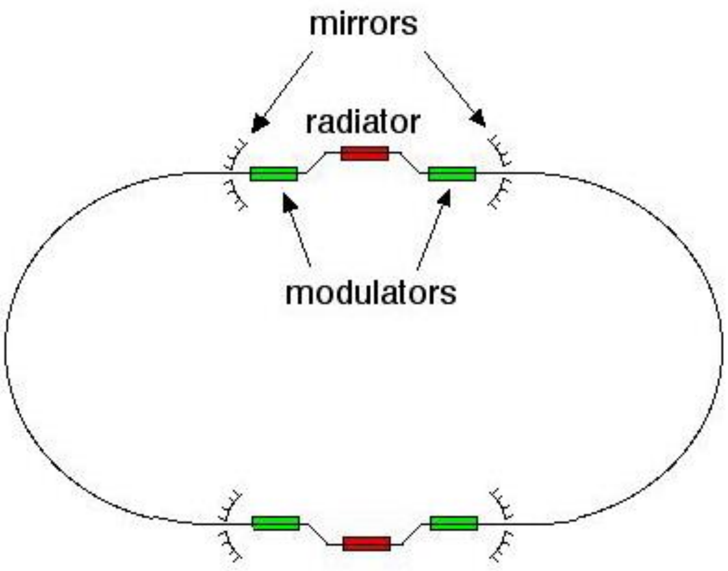
In the proposed SSMB scheme, the ring consists of superperiods. One radiator at resonant wavelength λ_r, sandwiched between two modulators that are laser seeded at resonant at λ_m = integer x λ_r

The beam is microbunched around the entire ring. R_{56}'s are momentum compaction factors.



A schematic of a facility with two SSMB radiation tools.

- A radiator is an undulator that resonates at the desired radiation wavelength λ_r (13.5 nm for EUV, for example). This is where coherent radiation is emitted.



- A modulator is an undulator resonant at wavelength $\lambda_m = M\lambda_r$ where M = 15-20.

- The modulators "seeded'' with a seed laser with wavelength λ_m . By the action of this seed laser, the electron beam will be steady-state microbunched with bunch spacing λ_m.

- Around the seed laser, two high-reflectivity mirrors form a laser cavity.

- Synchronization of the seed laser pulses and electron bunches at both of the modulators.

- The SSMB radiation is naturally very clean:

  narrow band (~0.5%)
  narrow divergence angle (~0.1 mrad)
  high average power in cw, but low peak power
  little radiation concerns.

Required hardware:

- a house-size conventional electron storage ring ~1 GeV
- three 3-m undulator magnets
- an UV seed laser (not EUV) with corresponding mirrors

Cost can be a small fraction of a 1-kW superconducting FEL with ERL.

Required technologies mature, but needs R&D to integrate:

- Electron storage rings
- High power cw laser

SSMB can be scaled to a range of frequencies from IR to EUV.

Multi-kW IR or DUV potential research tools for atomic or molecular physics, 1-kW EUV useful for the industry.

Assuming 100% filled rings:

		IR SPEAR3	DUV SPEAR3	EUV dedicated ring	
E_0	beam energy	900	900	580	MeV
C	ring circumference	234	234	100	m
α_C	ring mom. comp. factor	1.9	0.57	0.16	10^{-6}
I_0	average beam current	8.5	4.7	1.12	A
L_m	modulator length	3.7	3.2	3.4	m
λ_m	seed laser wavelength	13.2	3.5	0.37	μm
P_{seed}	seed laser power	15	15.7	11	kW
L_r	radiator length	3.5	3.3	3.54	m
λ_r	SSMB rad. wavelength	0.94	0.205	0.0133	μm
P_r	SSMB radiation power	85	41	4.06	kW

Notes:

- The high beam current I_0 assumes 100% filled rings, yielding (average, cw) 85 kW (0.94 um), 41 kW (0.205 um), and 4.06 kW (0.0133 um).

- In actual applications, partial filling (as low as 1% as needed) may suffice and the radiation power is reduced proportionally. Conversion efficiency stays ~30%.

- Three cases demand increasingly small values of momentum compaction factor α_C, and thus are expected to require increasingly demanding operational care of the storage rings. EUV is the hardest.

- The SSMB mechanism has only existed on paper and on computer simulation studies. Feasibility is not established. A proof-of-principle test on an existing storage ring is necessary step to go further.

Laser Power considerations:

- The seed laser power imposes the practical limitation. Reducing the filling is possibility, e.g. 10% filling ➔ 400 W EUV.

- The high seed laser power results from $\sigma_{laser} >> \sigma_{electron}$. The laser power is mostly wasted. It can be reduced if the modulator can be divided into subsections (synchronized).

- Another possibility is to invoke a dielectric channel to confine the laser power as similar to the SLAC laser acceleration experiments.

- Trade-offs between laser power and mirror reflectivity. Variations of the SSMB scenario include extreme cases without the mirrors or without the seed laser.

Proof-of-principle test proposal

We try to use the existing storage ring SPEAR3 as a prototype for a PoP test. One strong limitation is that the straight section length is limited to 4.7 m. The tests use relaxed parameters, and aim for IR radiation (not EUV).

Three operation cases are considered in the PoP test. All with partially filled ring with the conventional microwave rf turned on.

1. With a seed laser and the mirror cavity
2. Without a seed laser but with a mirror cavity
3. With a seed laser but no laser cavity

Not (yet) considered is the option using guided dielectric laser.

Where does this leave SSMB for EUV?

Plus side:

Potential for high average power in IR, DUV, EUV

Based on mature technology

Clean, compact, no radiation concern

Down side:

Still R&D to integrate systems

Technical issues to resolve (laser/cavity power, ring precision operation)

Need community effort. Academics can go only so far. Industry may/must provide the drive to move forward effectively.

Collaborators: Daniel Ratner, Xiaobiao Huang

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